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Abstract:
The Global Position System (GPS) and the Global Navigation Satellite System (GLONASS) are based on a satellite system. Much work has been carried out on a non-satellite positioning system using the existing Global System of Mobile Communications (GSM) infrastructure. This leads to a GPS-GSM positioning system that manufacturers claim to reliably locate a mobile phone down to resolutions of less than 125 m. The requirement needed to achieve such a resolution with a GPS/GSM positioning system is to have three GSM base stations in a 30 km area. This requirement is difficult to obtain especially in rural areas. The work carried out in this paper shows how to integrate digital audio broadcast (DAB) transmitters with GSM base stations for positioning systems. This novel DAB-GSM hybrid positioning system can reach an accuracy of 40 meters

Index Terms:
Global Positioning System cellular radio digital audio broadcasting radio direction-finding radio transmitters DAB transmitters DAB-GSM hybrid system GLONASS GPS/GSM positioning system GSM infrastructure Global Navigation Satellite System Global Position System Global System of Mobile Communications OPNET software package accuracy accurate vehicular positioning base stations digital audio broadcast transmitters mobile phone location nonsatellite positioning system rural areas satellite system

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Accurate Vehicular Positioning using a DAB-GSM Hybrid System

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Abstract – The Global Position System (GPS) and the Global Navigation Satellite System (GLONASS) are based on a satellite system. Much work has been carried out on a non-satellite positioning system using the existing Global System of Mobile Communications (GSM) infrastructure. This leads to a GPS-GSM positioning system that manufacturers claim to reliably locate a mobile phone down to resolutions of less than 125 m [3]. The requirement needed to achieve such a resolution with a GPS/GSM positioning system is to have three GSM base stations in a 30 km area. This requirement is difficult to obtain especially in rural areas. The work carried out in this paper is how to integrate Digital Audio Broadcast (DAB) transmitters with GSM base stations for positioning systems. This novel DAB-GSM hybrid positioning system can reach an accuracy of 40 meters.

I. Introduction

GSM is a narrow-band system that does not have a sufficiently accurate clock required for precise geographical location measurements. Consequently, techniques that require good time-based synchronization, such as Time Of Arrival (TOA) [3] and Time Difference Of Arrival (TDOA) [3], cannot provide sufficient accuracy by themselves. Similarly, the sensitivity of the GSM signal to interference (multi-path, Doppler shift etc.) also provides poor angular information due to extensive scattering, rendering schemes such as Angle of Arrival (AOA) [3] difficult to implement and inherently expensive.

DAB is a single frequency network (SFN), being broadcast from a multiplex. One National multiplex frequency carries all of the national services. This means that national stations appear at the same place on your dial anywhere. Subsequently, all DAB transmitters send the same data bits (in a 1.536 MHz RF channel), on the same frequency (225 MHz in UK) and at the same time.

Given this single frequency requirement, synchronization issues are of paramount importance, hence a GPS clock is used to synchronize all of the DAB transmitters. It is this timing precision which we have exploited using TDOA techniques, to provide accuracy in the range of tens of meters.

The Coded Orthogonal Frequency Division Multiplex (COFDM) [5] modulation scheme utilised by DAB further improves the usability of this form or radio source for positioning purposes. COFDM is considered to be a good modulation scheme, as in its four different modes of operation each have their own predefined guard interval and sub-carrier insertions. This offers a very good robustness, making it capable of handling echoes and Doppler shifts resulting from transmitter separation distance and mobile receiver speed.

Since DAB transmitters are not numerous for precise triangulation, this paper will also show how signals from GSM base stations could be used to ensure the performance of the positioning system.

DAB can only provide a one-way link, i.e. only down-link (from base station to mobile), hence only navigation could be considered if only DAB were to be used in isolation. However, with the combined system proposed in this paper, GSM would provide the return up-link path (from mobile to base station), facilitating such services as emergency help or breakdown.

In section II, GSM and DAB positioning techniques are outlined, with the performance and limitations of these two techniques investigated.

Section III discusses a method of combining DAB and GSM together with complexity issues involved in this novel fusion.

Finally, in section IV we present an analysis of the simulation results attained for the various positioning systems investigated.

II. DAB and GSM Positioning Systems

The most appropriate location technique that could be utilised with the DAB system would be TDOA. The efficient COFDM modulation scheme, adopted by DAB, can cope with many kinds of interference; including multi-path which is arguably the most destructive phenomenon in radio communications. In addition, the 10 MHz-GPS clock integrated into the transmitted signal supplies accurate and crucial synchronisation data to the DAB transmitters. Finally, its wide bandwidth of 1.5 MHz allows the receiver to obtain good time resolution (approx. 588 ns) for correlation purposes.

GPS
RX

return
RX

The Transmitter Identification Information (TII) tells the mobile receiver of the signal source. From the receiver's database it is able to correlate the received TII sequence with the local one, deducting the relative time delay and as a result making accurate TDOA measurements possible.

As DAB transmissions are only in the 'down-link' direction, a DAB-based positioning system could only be used to provide positional information to the user (e.g. the car driver) for navigation purposes. By incorporating the GSM network into the system, Short Message Service (SMS) data could be sent via the GSM 'up-link' to send such information as the Public Safety Answering Point (PSAP) via the Mobile Switching Centre, in the event of an emergency.

Operating within its current specifications, a GSM mobile could only be located to within 554 m [4], due to its bit-based resolution (3.69 μs/bit). This is without even considering multi-path or Geometric Dilution of Precision (GDOP), which would further diminish such accuracy.
By breaking down the bit resolution by a factor of 1/4, or even 1/8 (the level of resolution attended by a DAB receiver), and using multipath rejection algorithms, the requirements of a good positioning system can be met. This could be achieved through a transmission burst, using the correlation of the local and received training sequences, located in the middle of the burst. However, the question arises; Which channel to use?
One possible solution would be the utilisation of Traffic Channels (TCH). However, these are subject to discontinuous transmission and reception, power control and frequency hopping, which may affect the accuracy of location measurements. A viable alternative to the Traffic Channels are Control Channels. These are not subject to such problems and hence are a good resource for positioning purposes.
A further important aspect to consider is the repetition rate of the channel; as more frequent measurements imply greater accuracy. Here, the Broadcast Control Channel (BCCH) appears to be the most suitable for positioning purposes as it occurs every 236 ms, supplying the base station identity to the mobile station.
As very accurate transmitter synchronisation is necessary for high resolution TDOA location measurements, either GPS time transfer receivers could be placed at each GSM base station, or, some form of base station synchronicity information could be supplied via a short message service (SMS) or paging service.

III. Combined DAB-GSM Positioning

In order to employ TDOA techniques in a hybrid DAB-GSM system, all of the DAB transmitters and GSM base stations would have to be precisely synchronised. Obviously, this would be very costly and almost impossible to implement. Even if all of the GSM base stations were to be tightly synchronised together (via the implementation of a GPS clock for example), this would not imply that the DAB transmitters were in synchronisation with the GSM ones.
In addition, the repetition rates of the respective signals considered for each system (TII for DAB and BCCH for GSM) are different (192 ms and 236 ms respectively).
Taking these problems at face there appears to be no solution. However, if we consider transmitter, four or more transmitters instead of the usual minimum of three, a solution can be hatched.
However, before our methodology is examined, firstly we must investigate the basic principals of TDOA using a three transmitter configuration (see Figure 1).

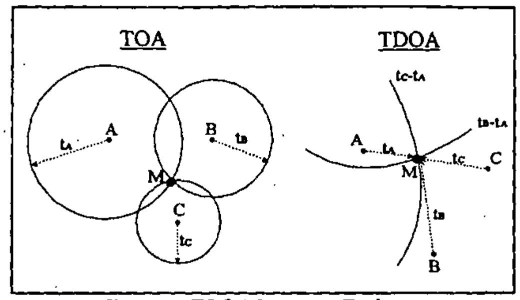

Figure 1: *TDOA Location Technique*

In an ideal terrain-less world, only three synchronised transmitters A, B and C are needed in order to locate exactly a fixed receiver. If the receiver is moving, its position can only be approximated due to the distance travelled while TDOA measurements are taken. Hence, the faster the mobile is moving, the greater the error will be. So the use of more than three transmitters (if available) is better when pinpointing 'moving objects'. Nevertheless, receiver speed does not affect measurement accuracy greatly, since it never travels anywhere near to the speed of light (3.10^8 m.s^{-1}).
The TDOA technique is based on a relative time reference (as opposed to the absolute time reference used for the TOA technique). Unlike TOA, that uses three circles (Figure 1), TDOA basically uses two hyperbolae of constant propagation time difference. Figure 1 suggests t_A as the relative time reference used by both hyperbolae (t_B - t_A and t_C - t_A). If all three transmitters are tightly synchronised together, then the accuracy is likely to be very good. But, if only one is not, this would incur a dramatic inaccuracy due to the fact that radio waves travel at the speed of light. Thus, if we assume its delay (compared to the two others) to be only 1μs, it would imply a 300 m degradation (1μs × 3.10^8 m.s^{-1})! The other timing problem to consider when combining DAB and GSM with this configuration is the repetition rate of the respective signals used for positioning purposes as they differ by 44ms (236ms – 192ms).
One way to cope with these timing problems would be to inform either the DAB transmitters or the GSM base stations of the timing offset. This would mean the installation of either a GSM receiver or a DAB receiver at the respective sites. Even supposing this were feasible, the authors could not see what the DAB and/or the GSM manufacturers would gain with the setting up of such a costly network infrastructure. Consequently, another approach has to be found.
An approximated locus can be obtained from a set of two or more hyperbolae, each defining a constant time difference. The (standard) TDOA technique is based on the fact that transmitters are all synchronised together. The most simple case and likely (because of the coverage problem) is to consider a set of three synchronised transmitters, forming just two hyperbolae. One way is to get a set of two different pairs of synchronised transmitters (i.e. two DAB transmitters and two GSM base stations). It is indeed practically feasible to obtain two 'independent' hyperbolas (Figure 2); one

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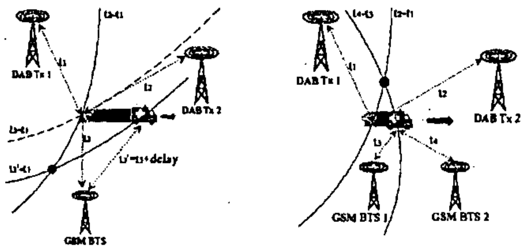
from the pair of synchronised DAB transmitters, the other from the pair of synchronised GSM base stations. It would probably not be as accurate as using three DAB transmitters (or maybe three GSM base stations) but that would resolve the problem of coverage that TDOA is sensitive to (see Figure 2).



(a) (b)

Figure 2: *The use of another GSM Base Station*

In addition to the use of two GSM base stations instead of one (Figure 2a), the previous configuration has another main difference. Since both hyperbolae are made up from a pair of synchronised transmitters there is no time offset interpreted by the receiver side as a propagation delay. Nevertheless, since both hyperbolae are not obtained simultaneously, it induces a time delay due to the 'pseudo-synchronisation' and the difference of the signal repetition rate. Note the worst case is a 96 ms delay, that is half the TII repetition rate (192 ms / 2). However, this delay is tied with the speed of the vehicle, instead of the speed of light. Indeed, if the vehicle is assumed to run at 100 km/h, it would imply an additional error of about 2.7 m (100 km × 96ms / 3600) if the worst case were to be taken.

Mathematical Approach

Much research has been conducted to find adequate formulae for hyperbolic TDOA location systems. Unfortunately, most of the formulae are either too complicated, and hence inadequate for quick computation, or too simple, providing poor results. Y. T. Chan and K. C. Ho [6] suggest a formula (in terms of a relative reference propagation distance r_1) that can be applied that considers three transmitters and one receiver.

$$\begin{bmatrix}x\\y\end{bmatrix} = -\begin{bmatrix}x_{2,1} & y_{2,1}\\ x_{3,1} & y_{3,1}\end{bmatrix}^{-1} \times \left\{\begin{bmatrix}r_{2,1}\\ r_{3,1}\end{bmatrix} r_1 + \frac{1}{2}\begin{bmatrix}r_{2,1}^2 - K_2 + K_1\\ r_{3,1}^2 - K_3 + K_1\end{bmatrix}\right\}$$

Where (x, y) is the unknown position of the mobile receiver, (x_i, y_i) is the known location of the relative transmitter and r_i is the relative propagation distance, with i = 1, 2 or 3, and:

$$r_{i,1} = r_i - r_1 \qquad K_i = x_i^2 + y_i^2$$

$$x_{i,1} = x_i - x_1 \qquad y_{i,1} = y_i - y_1$$

$$r_i = \sqrt{(x_i - x)^2 + (y_i - y)^2}$$

Thus, we can measure a mobile's position as (x and y) in a 2-D plane.

The equation above is not applicable for the combined positioning system since two different pairs of transmitter are used instead. However, Y. T. Chan and K. C. Ho also give a sole equation to define mathematically a single hyperbola [6] from which the ordinates can be obtained:

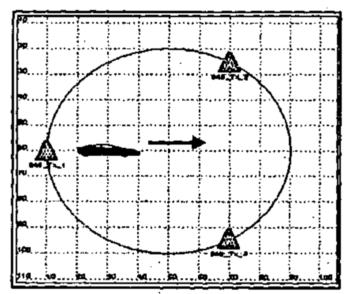
Since the actual position of the mobile is known, it is easy to calculate the root-mean-square deviation (drms) which evaluates to the performance of any location technique:

$$drms = \sqrt{(x_{meas.} - x_{real})^2 + (y_{meas.} - y_{real})^2}$$

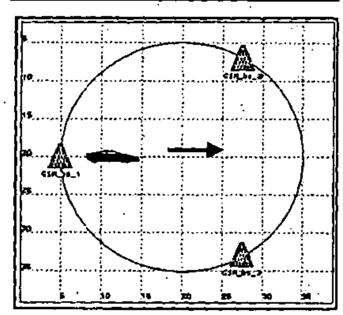
Modelling

Three network configurations seen in Figure 3, were simulated using the OPNET software package. The first one (i) models a DAB positioning network. Indeed, it makes sense to start with DAB since it is not sensitive to interference and consequently there is no need to study multi-path effects. Then, GSM is studied (ii), which implies going through multi-path analysis. And then finally, both systems are combined in (iii).

(i)



(ii)



(iii)

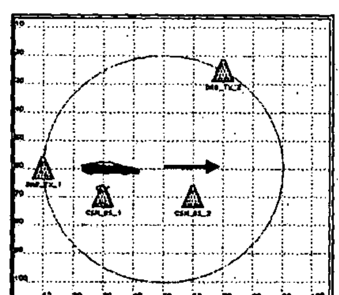


Figure 3: *DAB, GSM and Combined Network Models*

IV. Simulation Results and Analysis

DAB Positioning Accuracy:

As DAB uses COFDM, there is no need to study such a system in a multipath environment since such a modulation scheme has been revealed to be relatively immune to interference. A configuration where the DAB transmitters are 70 km apart has been considered for the use of the simulation and ideal radio channel selected. The obtained results are shown in Figure 4. Note that drms is root-mean-square deviation.

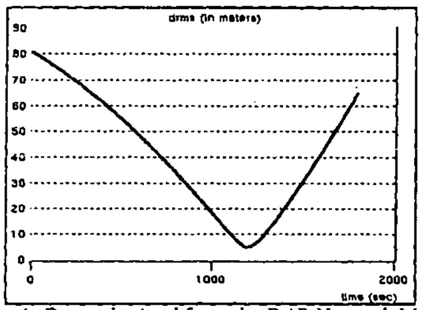


Figure 4: *Drms obtained from the DAB Network Model*

Perhaps, the first thing that can be noticed is that the accuracy is not constant, even with an ideal radio channel. Surprisingly, the best accuracy of 5m is located at two thirds (instead of one third as it could have been thought) of the mobile trajectory (Figure 3i), which corresponds to the middle of the line crossing the right-hand-side transmitters on the network model. Moreover, the worst accuracy (80m), when the mobile receiver is at the closest point to the left-hand-side transmitter, is still really good when you consider the distance separating the transmitters is 70km. Then it drops until reaching the maximum accuracy before rising up again. This is due to what is called the Geometric Dilution Of Precision (GDOP). In other words, it is depending on the geometry of the transmitters and the relative position of the mobile receiver within this geometry.

GSM Positioning Accuracy:

Unlike DAB, GSM is sensitive to radio interference of which the effect is dependent on the environment. Therefore, the simulation study suddenly appears to be more complex. Indeed, the study of radio interference is not well defined. The only means that scientists provide to engineers are statistical-based formulae, often derived from empirical measurements.

TDOA, as a time-based positioning technique, is sensitive to multipath delay, often generalised as 'delay spread'. Therefore, only multipath delay can be used to model differing environments; the studied cases will be limited to ideal, rural and urban environments.

N.B.: The ideal, rural and urban environments have been modelled with 0, 0.5 μs and 5.0 μs multipath delay respectively.

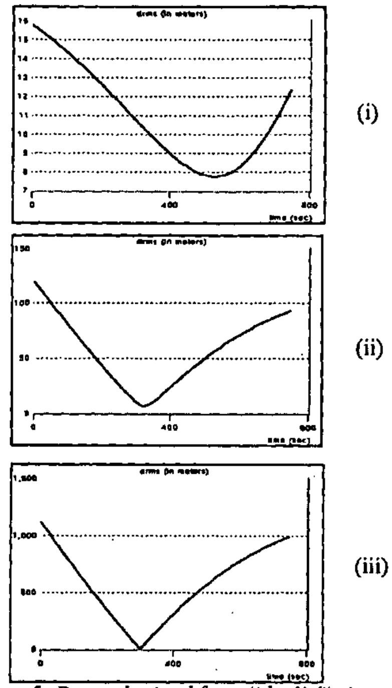


Figure 5: *Drms obtained from 'ideal' (i), 'rural' (ii) and 'urban' (iii) GSM Network Model*

As it can be seen from the plots, the accuracy of all three vary in a similar way due to GDOP. However, the minimum drms occurs close to the two thirds of the trajectory for the ideal case (i), and at its third (i.e. at the intersection point of the medians of the equilateral triangle defined by the three transmitters) for rural (ii) and urban cases (iii).

The insertion of multipath delay can affect dramatically the positioning accuracy, depending on how high it is. Thus, the accuracy varies from about 16 m to nearly 8m in an ideal environment. This improved level of accuracy is due to a smaller distance (25km) separating the GSM base stations compared to 70km for the DAB transmitters.

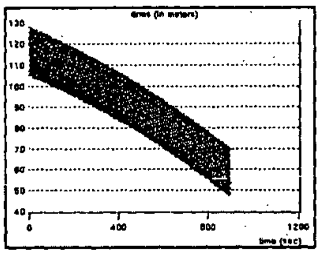
However, such definition is never achieved in a real environment since GSM, unlike DAB, is sensitive to interference. This begins at about 120m in a rural environment and about 1.1km in urban surroundings. However, it drops until reaching the intersection point of the medians where the level of accuracy is surprisingly similar to the ideal environment. Therefore, GDOP can have a similar effect as multipath.

N.B.: The worst GDOP effect is obtained when the transmitters are in line. This case can occur in a real environment; e.g. the GSM base stations are placed along a motorway. This configuration cannot happen for DAB since its transmitters are further apart and less numerous.

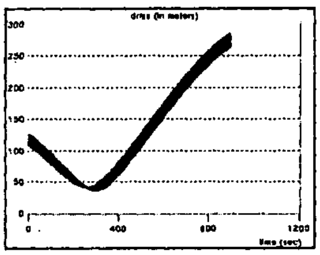
Combined DAB-GSM Positioning Accuracy:

Like GSM positioning, multipath has to be considered when studying the level of accuracy obtained from a combined DAB-GSM system.

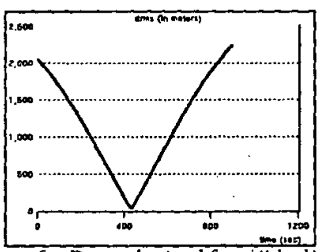
As it can be seen from the first plot (Figure 6 i), the accuracy of such a system without multipath is good: around 130m at worst, improving to about 50m. However, it is clear that the minimum drms is expected to be further than where the mobile stops. Indeed, the best accuracy is obtained where the GDOP effect is minimum, and the mobile has not reached this point due to the network configuration.



(i)



(ii)



(iii)

Figure 6: *Drms obtained from 'ideal', 'rural' and 'urban' Combined DAB-GSM Network Model*

Even with multipath, the accuracy for rural environment (Figure 6 ii) is 280m at worst and about 40m at best. Like GSM positioning during multi-path, deteriorates the accuracy dramatic (to more than 2km) in an urban environment (Figure 6 iii). However, it is worthwhile noting that this combined configuration has been designed to counter-balance the DAB coverage problem. In an urban environment, DAB transmitters are numerous enough to support positioning by themselves, hence a very good accuracy (tens of meters) would be obtained, as the simulation results showed.

Thus, it has been seen that another important factor influencing the location accuracy of a TDOA system is Geometric Dilution Of Precision. When developing a positioning system, designers aim to minimise the GDOP; this can contrast with the design criteria for mobile communication systems where the goal is communication service provision. The geometry can have a significant impact on location accuracy, equal to or greater than the impact of multipath.

V. Conclusion

Much work has been carried out in the field of terrestrial positioning system based on the GSM network. This GPS-GSM positioning system is a cheap alternative to the existing GPS and GLONASS systems. This system can achieve a resolution of less than 125m [3]. However in rural areas, where the GSM infrastructure is sparse, this resolution can not be obtained. This is due to the fact that the GPS-GSM system requires three GSM base stations in an area of 30 km to function adequately. The work carried out in this paper was to investigate the methodology of integrating DAB transmitters to the GPS-GSM system in order to obtain adequate level of resolution in rural areas. This new DAB-GSM hybrid system was mathematically modelled using the OPNET software package. The results show that with such a hybrid system an accuracy of 40 meters can be reach. This makes such a system suitable for positioning in rural areas, where only the GSM infrastructure is not sufficient.

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